LCA Methodology

The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection

Part 2: Selecting the Boundary Cut-off Parameter (Z_{RMEE}) and its Relationship to Overall Uncertainty

Marlo Raynolds[1], Roydon Fraser[2], David Checkel[3]

[1]University of Alberta, Dept. of Mechanical Engineering, 4-9 Mechanical Engineering Building, Edmonton, Alberta, T6G 2G8, Canada
[2]University of Waterloo, Waterloo, Canada
[3]University of Alberta, Dept. of Mechanical Engineering, Edmonton, Alberta, T6G 2G8, Canada

Corresponding author: Marlo Raynolds; e-mail: raynolds@pembina.org

Abstract. Life-Cycle Assessment (LCA) is a decision analysis tool used to compare alternatives to providing a given product or service. To ensure a fair comparison, LCA must select system boundaries in a consistent manner.

The Relative Mass-Energy-Economic (RMEE) (pronounced 'army') of system boundary selection is a practical and quantitative method of defining system boundaries. RMEE compares each input to a system with the system's functional unit on a mass, energy and economic basis. If this ratio of input to functional unit is less than a selected "cut-off" (defined as 'Z_{RMEE}') then the input is excluded from the analysis and all unit processes upstream of that input are outside the system boundary. Ignoring unit processes outside the system boundary limits the size of the LCA analysis but adds a source of uncertainty for the overall results. The lower the value of the Z cut-off ratio the larger the system boundary is, resulting in a greater number of unit processes.

The relationship between the Z_{RMEE} cut-off and the uncertainty introduced to the results of an LCA are explored. The relationship between Z_{RMEE} and uncertainty has been derived by analyzing 800 random systems of four different types, with the RMEE method of system boundary selection applied at different Z_{RMEE} values. The uncertainty introduced to the overall results increases as the selected Z_{RMEE} becomes larger.

Keywords: Comparative assertions; LCA; Life Cycle Assessment (LCA); relative mass-energy-economic (RMEE); RMEE; system boundary selection

1 Introduction

Life Cycle Assessment (LCA) used as an aid to decision making compares service or product alternatives based on their life-cycle economic costs and/or potential environmental impacts. A key step in any life-cycle assessment is to break each alternative into a collection of unit processes representing the life-cycle system. In theory, each system is a col-lection of hundreds of thousands of unit processes. That is, one could argue any service or product is interconnected with the entire economy. To be of practical use, LCA must draw system boundaries and exclude certain unit processes from its analysis. To make a fair comparison between alternative products or services, one must ensure *similar* boundaries are selected for each system. The first question is "how does one select 'similar' system boundaries"? The second important question is, "what effect does the selection of my system boundary have on the uncertainty in my results"?

An answer to the first question, "how does one select similar system boundaries?", is provided by the related paper which presented "The Relative Mass-Energy-Economic (RMEE) Method of System Boundary Selection – A Means to Systematically and Quantitatively Select LCA Boundaries – Part 1"[1]. The current paper, Part 2, focuses on the second question, "what effect does system boundary selection have on the uncertainty in the results of an LCA?". Therefore, the *objective* is to quantify the relationship between the system boundary cut-off parameter (Z_{RMEE}) in the RMEE method and the boundary-related uncertainty in the final results of an LCA.

For a review of the existing methods for system boundary selection and a discussion on the requirements of a useful and rigorous method refer to Part 1 [1] which includes a detailed description, justification, and example of the RMEE method. The present paper briefly describes the RMEE method, but focuses on developing the relationship between the RMEE system boundary cut-off parameter (Z_{RMEE}) and the uncertainty in the overall results of an LCA due to system boundary selection. The relationship between Z_{RMEE} and uncertainty is presented graphically and in tabular form for further application. Finally, the implications of the RMEE method for system boundary selection are shown through an example comparison of two systems. This example demonstrates how the mean environmental output of one system can be compared to the mean of a competing system to calculate a confidence one system outperforms another.

2 The Relative Mass-Energy-Economic (RMEE) Method

What makes the RMEE method different from other methods of system boundary selection is that it is based on examining the ratio between inputs to a unit process and the functional unit. In other words, the method considers each input and asks "How relevant is this input to the functional unit?". If the input is considered significant to the functional unit, then the upstream unit process providing the input is included inside the system boundary of the LCA. If the input is considered insignificant to the functional unit, the upstream unit processes providing the input are "cut-off", that is they are considered outside the system boundary of the LCA. In the RMEE boundary selection method, "significance" is defined by whether the ratio of the input to the functional unit exceeds a chosen value called the Z_{RMEE} cut-off ratio. If the ratio of input to the functional unit is greater or equal to the Z_{RMEE} cut-off, then the upstream unit process is included in the system boundary. If the ratio is less than Z_{RMEE}, the upstream unit processes are excluded from the system boundary. Comparison between the input and Z_{RMEE} is made using three ratios: mass, energy, and economic value. As a result, the mass value of each input is compared to the mass of the functional unit, the energy content of each input is compared to the energy content of the functional unit, and the market value of each input is compared to the market value of the functional unit. If *any* of the three ratios is greater than the Z_{RMEE} cut-off then the upstream unit processes are included in the system boundary. In the end, the RMEE method provides a repeatable and quantitative method of selecting system boundaries for LCA studies comparing energy or product systems with primary interest in combustion related air emissions.

Extracted from Raynolds et al. [1] the steps to apply RMEE are as follows:

1. Identify and define the functional unit for the LCA.
2. Calculate the total mass, energy, and market economic value of the functional unit. Define these as: M_{Total}, E_{Total} and $\$_{Total}$ respectively[1].
3. Define a system boundary "cut-off" ratio (Z_{RMEE}). (Selection of an appropriate Z_{RMEE} is the subject of the remainder of this paper).
4. Begin at the unit process closest to the functional unit, with inputs a, b, c, ..etc.. Quantify the mass (M_i), energy (E_i) and economic value ($\$_i$) of each input (i = a,b,c, ...). Inputs without a meaningful mass or energy value are assigned zero (e.g. electricity is assigned zero for mass, while most process chemicals are assigned zero for energy since their purpose is not an input to energy). Document the sources of data, calculations, and assumptions made.
5. Calculate $M_{Ratio} = M_i/M_{Total}$, $E_{Ratio} = E_i/E_{Total}$, and $\$_{Ratio} = \$_i/\$_{Total}$. This defines the relative contribution of each input by mass, energy and economic value to the functional unit.

6. If M_{Ratio}, E_{Ratio}, or $\$_{Ratio}$ is greater or equal to Z_{RMEE}, then the upstream unit process which provides this input is to be included in the system boundary. If neither M_{Ratio}, E_{Ratio}, nor $\$_{Ratio}$ is greater than Z_{RMEE}, then the input is considered "cut-off" and the upstream unit processes supplying it are not included in the system boundary.
7. Repeat the process for each input of all unit processes included in the system, until all inputs are "cut-off".
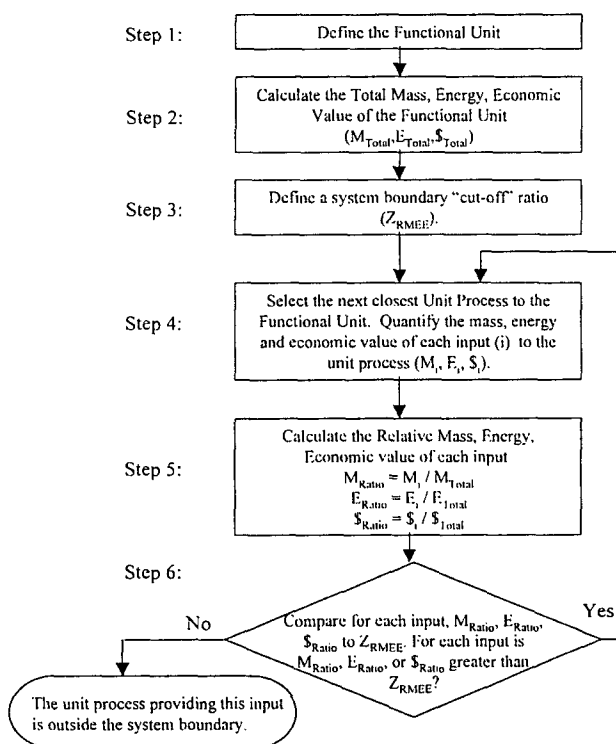
The procedure is shown in **Fig. 1**.

Fig. 1: The RMEE method of life cycle system boundary selection for LCA [1]

The end result of the RMEE system boundary method for any LCA system is a quantified system boundary determined by the chosen Z_{RMEE} ratio. Two or more systems, which provide the same functional unit and with the same Z_{RMEE} cut-off can then be compared because they have similar system boundaries. The questions not answered by Raynolds et al. in Part 1 [1] were: "How does one select Z_{RMEE}?" and "What degree of uncertainty does the system boundary selection introduce to the overall results?". The remainder of this paper presents answers to these two questions.

3 Selecting the Appropriate Z_{RMEE} Cut-off Ratio for RMEE

The Z_{RMEE} cut-off defines the system boundary of an LCA. With a smaller Z_{RMEE} ratio, the system to analyze becomes larger. As Z_{RMEE} gets larger, more unit processes are left out of the system, resulting in a smaller analysis problem but more uncertainty as to the 'real' environmental performance of a system. To be able to use LCA for decision making it is important to understand the uncertainty in the results [2,3].

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[1] The market value of any product or service may fluctuate due to changes in the economy. However, LCA analysis is generally based on a time and technology "snap-shot" of a system. A current static value should be used for the market value of products or services for the RMEE method. When using LCA to assess future projects it is appropriate to use the values generated through an economic analysis of the project.

3.1 Method to derive a relationship between Z_{RMEE} cut-off and uncertainty introduced into LCA due to system boundary selection

As the Z_{RMEE} cut-off ratio increases, the boundaries decrease and a greater amount of environmental outputs is not included in the final LCA results. At $Z_{RMEE} = 0$ the entire theoretical system is analyzed and accounts for all environmental outputs. In other words, as Z_{RMEE} increases, the fraction of the true total environmental outputs measured by the LCA decreases. At $Z_{RMEE} > 0$, not all unit processes are accounted for and therefore the true total of environmental outputs is not measured.

To find the relationship between Z_{RMEE} and the fraction of total environmental output a stochastic modeling study was completed. Eight-hundred random LCA systems were generated and evaluated at different Z_{RMEE} values using a LCA software package developed by the principal author. Each system was randomly generated using rules to generate a realistic distribution of mass, energy and economic inputs throughout the system. Four different types of systems were evaluated, each type defined by the nature of the functional unit produced ($\rightarrow$ Table 1). Within each type of system, systems with 50 and 100 unit processes were used. The assumption was made that these systems of 50 and 100 unit processes represent the true total system. The method for generating random systems is described below.

Random System Generation
The type of functional unit provided defines each type of system, described in Table 1. Type I is a product with a relatively high heating value (25,000 kJ/kg) and is relatively expensive for a fuel (1 $/kg). Type II is a lower cost fuel (0.25 $/kg) with a relatively high heating value (25,000 kJ/kg). Type III is a product with low heating value (5,000 kJ/kg) and medium cost associated with it (100 $/kg). An example of a Type III product might be a manufactured component or part. Finally, Type IV describes a functional unit with a low heating value (5,000 kJ/kg) but a high cost (1000 $/kg). Throughout the remainder of this paper each system type will be referred to by the nomenclature defined in Table 1.

For each type of functional unit, 200 systems were randomly generated: 100 systems with 50 unit processes, and 100 systems with 100 unit processes. Each system was generated by

starting at the functional unit and working upstream systematically adding unit processes to the system. To make each system as realistic as possible the following rules were used:

- The number of inputs to any unit process is from 1 to 6 with a triangular discrete probability distribution function, which gives 3 or 4 inputs the highest probability, and 1 or 6 inputs the lowest probability.
- The mass ratio of inputs to outputs for any unit process is from 1 to 5, meaning an optimal unit process could have 100% efficiency in mass transfer, whereas the worst unit process is one which requires 5 times the mass input to generate an output. The mass ratio is assumed to be uniformly distributed between 1 and 5.
- For each unit process, mass is conserved by assuming the combined total of input materials becomes either output products or environmental outputs (e.g. Environmental Outputs = Total Mass of Inputs – Total Mass of Products). These environmental outputs are assumed to be common combustion related emissions.
- The energy efficiency of a unit process is assumed to be uniformly distributed between 5% and 99% meaning in the best case a unit process will transfer 99% of its input energy to the product (the difference is lost to the environment).
- The energy per kilogram of any input or output is bounded between 0 and 50 MJ/kg. In other words, no material in the system can have a heating value above 50 MJ/kg.
- The market value of flows in each system is defined by a random rate of return for each unit process. The rate of return is assumed to be uniformly distributed between 0 and 20%. As a result, the Total Value of Inputs to a Unit Process = Total Value of the Product / (1 + Rate of Return).
- Co-products of a unit process are not generated for the random unit processes because it is assumed upstream inputs and environmental outputs have been allocated to each product. The resulting random system represents the allocation of inputs and environmental outputs to the primary product.

Evaluation of Random Systems
Each of the 800 random systems was evaluated at different Z_{RMEE} cut-off ratios in order to find a relationship between Z_{RMEE} and the fraction of the known total environmental output for any system. The total environmental output of each system was evaluated using a range of Z_{RMEE} cut-off ratios: $Z_{RMEE} = 0, 0.05, 0.10, 0.15, ... 2.0$. Each random system reacts differently with respect to how much of the

Table 1: The four types of random systems to be evaluated

System Type Number	Type of Functional Unit	Mass per unit of functional unit (kg/unit)	Energy per unit of functional unit (kJ/unit)	Market value per unit of functional unit ($/ unit)	Example	Nomenclature (Mass, Energy, Market Value)
I	Relatively expensive, high energy value	1	25,000	1	High value fuel or material with higher energy value, e.g. plastics	(1,25000,1)
II	Relatively low cost, high energy value	1	25,000	0.25	Low cost fuel, e.g. gasoline, ethanol	(1,25000,0.25)
III	Medium cost, low energy	1	5,000	100	Medium cost finished product or expensive material, e.g. automotive part	(1,5000,100)
IV	High cost, low energy	1	5,000	1000	High market value finished product, e.g. electronics components	(1,5000,1000)

known total environmental output is reported at different Z_{RMEE} values. Fig. 2 provides an example of three independent random realizations of Type II systems and their relationship between the fraction of environmental output and the Z_{RMEE} cut-off.

The "true" total of environmental output for each system is found in the case where $Z_{RMEE} = 0$, hence in Fig. 2 all three systems start with 100 percent of the environmental outputs at $Z_{RMEE} = 0$. As Fig. 2 shows, different random systems of the same system type are affected differently by varying Z_{RMEE} ratios. The measured output of some systems drops rapidly at low Z_{RMEE}, while others measure over 90% of the total environmental output even at $Z_{RMEE} \approx 2.0$. The objective here is to derive a trend between Z_{RMEE} and the fraction of total environmental output measured, by using large sets of random systems.

Each of the eight sets (50 and 100 unit process systems for each of the four system types) of 100 random systems were evaluated at Z_{RMEE} values ranging from 0 to 2 at increments of 0.05. Using these results a statistical evaluation was completed to determine if there is a significant difference between the eight sets of systems.

Comparison of Each Set of Random Systems

Fig. 3 shows a plot of the average result for each of the eight sets of systems. To test the significance of the number of
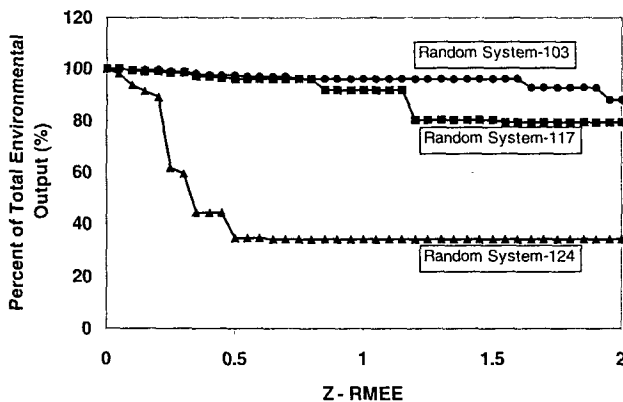

Fig. 2: An example of 3 Type II systems and the relationship between Z_{RMEE} cut-off ratio and fraction of the true total environmental output
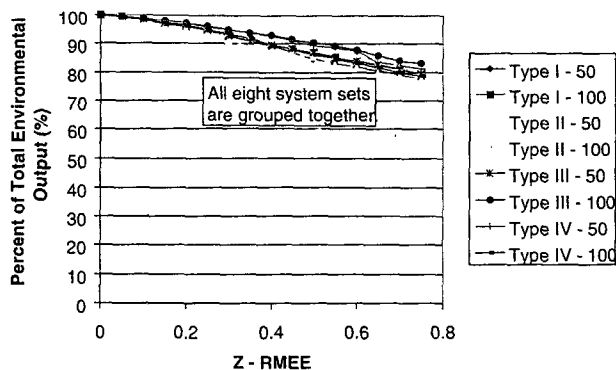

Fig. 3: Comparison of the mean relationship between Z_{RMEE} and the fraction of total environmental output for each set of 100 random systems

unit processes in a system, the mean of systems with 50 unit processes was compared to the mean of systems with 100 unit processes using T-statistic hypothesis testing.

The statistical test applied to the mean of each Z_{RMEE} value for each system type is shown in Equation 3.1. The Null Hypothesis (Ho) is defined as $U_{50} = U_{100}$ (the mean percent of total environmental output of a system with 50 unit processes is the same as the mean of a system with 100 unit processes for any given Z_{RMEE}). The Alternative Hypothesis (Ha) is $U_{50} \neq U_{100}$. The null hypothesis rejection region is defined as $T < -t_{\alpha/2}$ and $T > t_{\alpha/2}$, with significance level α. This is a two tailed statistical test with unknown variances and does not require equal variances between the populations [4]. Since 100 samples is relatively large, the normal distribution is assumed in the test by the law of propagation of errors [4]. Although the T statistic is designed for normal distributions it can be applied to non-normal distributions as long as both samples are large enough for the central limit theorem to be invoked [5].

$$T = \frac{U_{50} - U_{100}}{\sqrt{\dfrac{S_{50}^2}{n_{50}} + \dfrac{S_{100}^2}{n_{100}}}} \qquad (3.1)$$

U = Sample mean
S = Sample standard deviation
n = Sample size

The results of the statistical test at significance level $\alpha = 0.05$, show no evidence to reject the null-hypothesis. This means it is reasonable to assume the relationship between Z_{RMEE} and the percent of the true environmental output of a system is independent of the number of unit processes in the system. As a result, the sets of random systems with 50 and 100 unit processes were combined for each system type (Type I, II, III, and IV).

Next, a comparison between each of the four types of systems was completed to determine if all 800 random systems could be considered together. Fig. 4 provides an indication that the mean and 95% confidence intervals for each type of system are fairly closely grouped. To test this, the mean values of the four different types of systems were also compared using the statistical procedure in equation 3.1. The
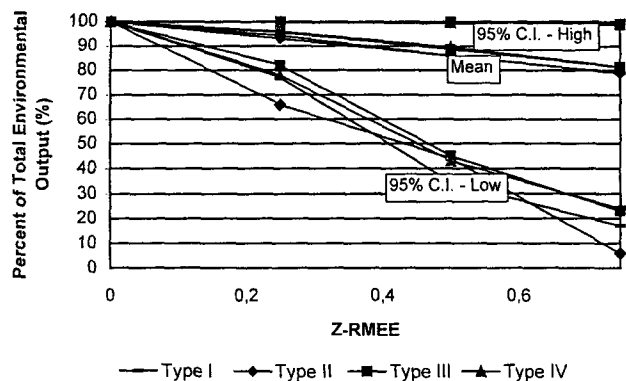

Fig. 4: Comparison of the mean and 95% confidence intervals for each of the four types of systems

objective was to evaluate whether there is a significant difference between types of systems (each type defined by the mass, energy and market value of the functional unit). The statistical test again showed no evidence to reject the null hypothesis that the mean values of each of the four system types (I, II, III, IV) are equal. As a result, it is a reasonable assumption to combine the 800 random realizations of four different types of systems in order to calculate a mean and 95% confidence interval for the relationship between Z_{RMEE} and the fraction of total environmental output.

3.2 Results: The relationship between Z_{RMEE} and fraction of total environmental output

The mean and 95% confidence interval for the fraction of total environmental output reported at different Z_{RMEE} values is shown in **Fig. 5**. This fraction of the total environmental output is defined as Y_{ZMean} with 95% confidence interval defined between Y_{ZHigh} (high value) and Y_{ZLow} (low value). **Table 2** provides the same results with additional information including the standard deviation and mode at each Z_{RMEE} value.
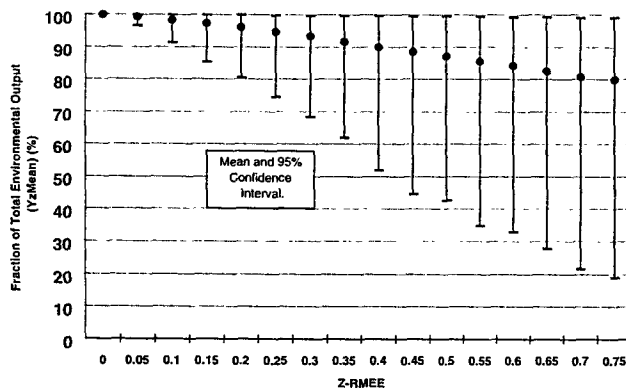

Fig. 5: Mean and 95% confidence interval for the percent of total environmental output (Y_{zMean}) reported at different Z_{RMEE} values

Beyond $Z_{RMEE} = 0.5$, the lower 95% confidence interval for the fraction of environmental output measured drops below 50%. Based on the author's experience, it is not recommended to use Z_{RMEE} values greater than 0.25 because too much uncertainty is introduced to the analysis. The Z_{RMEE} values of most interest are from 0.05 through to 0.25 where more than 90% of the total environmental outputs are likely to be within the system boundary, and the lower bound of the 95% confidence interval remains above 70%.

4 Application of the Results

The results presented in **Fig. 5** and **Table 2** show a relationship between Z_{RMEE} and the ratio of the true total environmental outputs (Y_{zMean}). This relationship can be used to estimate the uncertainty in results due to system boundary selection for real LCA analysis where the true environmental output is not known. Development of the relationship between Z_{RMEE} and Y_{zMean} has been made with common combustion related air emissions. The RMEE method is well suited for these emissions because there is a strong corelation between the three RMEE criteria (mass, energy and economic value) and combustion emissions [1]. For LCA studies wishing to investigate toxicity issues, RMEE is not recommended.

Define X_{zj} as the mean total value of a given environmental pollutant (e.g. greenhouse gases) calculated for a given system (j) with system boundaries defined by Z_{RMEE}. The value X_{zj} is the mean value of an environmental output calculated through a life-cycle inventory and will have a standard deviation and uncertainty due to data quality. Define the 95% confidence interval for X_{zj} as r_{data} (r_{data} represents the propagation of error throughout the system due to uncertainty in the data of individual unit processes and is best calculated using Monte Carlo Analysis (MCA) [2]). Then, using the Y_{zMean} value for the given Z_{RMEE} in **Table 2**, and equation 3.2, it is possible to calculate X'_{zj} (X_{zj} primed) as an approximation of the true total environmental output. X'_{zj} represents an estimation of the true environmental output for system j

Table 2: Mean and 95% Confidence Interval of the Fraction of Total Environmental Output for Different Z_{RMEE} values

Cut-Off Ratio (Z_{RMEE})	Percentage of True Total Environmental Output			Mode	Standard Deviation
	Mean (Y_{zMean})	High (Y_{zHigh})	Low (Y_{zLow})	m_{RMEE}	S_{RMEE}
0	100.00	100.00	100.00	100	0
0.05	99.38	99.97	96.67	99.90	0.93
0.10	98.37	99.96	91.40	99.51	2.52
0.15	97.29	99.93	85.33	99.45	3.86
0.20	96.16	99.90	80.50	99.30	5.32
0.25	94.74	99.85	74.60	98.78	7.05
0.30	93.40	99.81	68.50	97.42	8.66
0.35	91.74	99.76	62.00	97.33	10.40
0.40	90.16	99.70	52.00	97.12	11.89
0.45	88.58	99.63	44.67	96.13	13.40
0.50	87.09	99.57	42.67	95.52	14.62

by taking into account the unit processes outside the system boundary. This is an approximation based on observation from the 800 random systems modeled to derive the relationship between Z_{RMEE} and uncertainty in system boundary. his equation is based on the relationship between Z_{RMEE} and the fraction of total environmental output (→ Fig. 5, Table 2).

$$X'_{zj} = \frac{X_{zj}}{Y_{zMean}/100}\qquad(3.2)$$

X'_{zj} = Approximation of the true mean of an envonmental pollutant.

X_{zj} = Calculated environmental pollutant of system j with system boundary defined by Z_{RMEE}.

Y_{ZMean} = The mean percent of the true environmental pollutant an Z_{RMEE}.

In order to calculate the total uncertainty associated with the results of an LCI, the uncertainty due to system boundary selection must be combined with the uncertainty due to data in the analysis (r_{data}). Because the distribution of Y_{ZMean} is non-normal, normal distribution statistics can not be used for combining the uncertainty from data, with the uncertainty introduced due to system boundary selection. Fig. 6 illustrates the type of skewed distribution Y_{ZMean} follows. This distribution is typical for all Z_{RMEE} values.

To combine the uncertainty from data (r_{data}) with uncertainty introduced due to the distribution of Y_{zMean}, Monte Carlo Analysis has been used to calculate the mean and uncer-

tainty of X'_{zj}. Using equation 3.2, 1000 random variables from the distributions of X_{zj} and Y_{zMean} are selected to generate a distribution for X'_{zj}. From the distribution of X'_{zj} the mean and 95% confidence interval is calculated to provide a best approximation of the total outputs of an environmental pollutant in an LCA.

In order to complete the Monte Carlo Analysis on equation 3.2, a probability distribution function must be selected for Y_{zMean}. For this research, two probability distribution functions were tested and compared:

1. the distribution generated numerically from the 800 random systems (illustrated by Fig. 6), and
2. a normal distribution centered on the mean and truncated at Y_{zMean} equal to 100 with values greater than 100 placed at the upper boundary ($Y_{zMean} = 100$), as illustrated in Fig. 7.

The example below shows three things:

1. as Z_{RMEE} is reduced the total uncertainty is reduced,
2. the truncated-normal distribution provides a conservative estimate of the uncertainty when compared to the numerically generated probability distribution function, and
3. how to complete a comparison between two random systems – System B and System C, using the RMEE method. It is also shown how to estimate the probability the mean environmental outputs of one system is less than a competing system.

4.1 An example of applying the system boundary factor (Y_{zMean}) and system boundary uncertainty estimated by RMEE

For this example, two random systems were generated consisting of 100 unit processes. Both systems produce the same functional unit with a heating value (25 MJ/kg) and market value ($1/kg) (Type I). These systems have been called "System B" and "System C". For illustrative purposes, only greenhouse gas emissions are evaluated in this example.

The Relationship Between Overall Uncertainty and Z_{RMEE}
Fig. 8 and 9 illustrate the relationship between the Z_{RMEE} value and the change in mean greenhouse gas emissions and uncertainty for System B and System C. As the Z_{RMEE} value increases the analysis becomes less detailed and more unit processes or
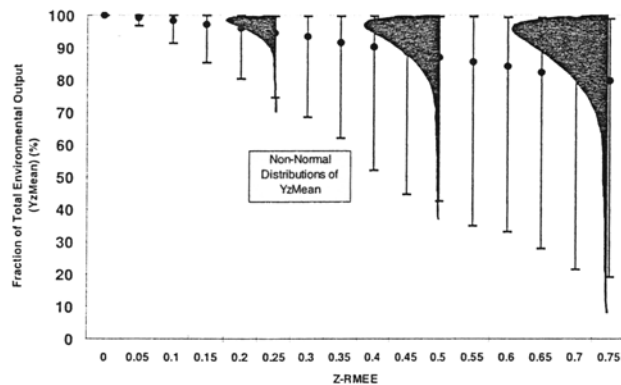

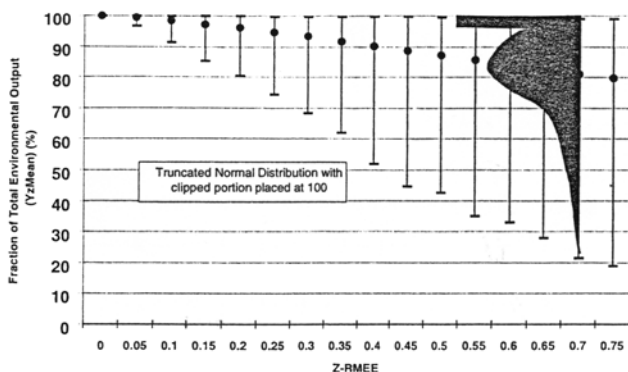**Fig. 6:** Illustration of the non-normal distribution of Y_{zMean}

Fig. 7: Illustration of the truncated-normal distribution used to approximate the numerical probability distribution function for Y_{zMean}
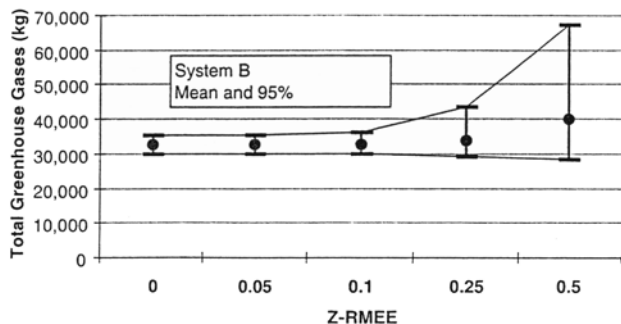

Fig. 8: The relationship between the Z_{RMEE} value and mean with 95% confidence interval for System B. At $Z_{RMEE} = 0$, the only source of uncertainty is from uncertainty in the data
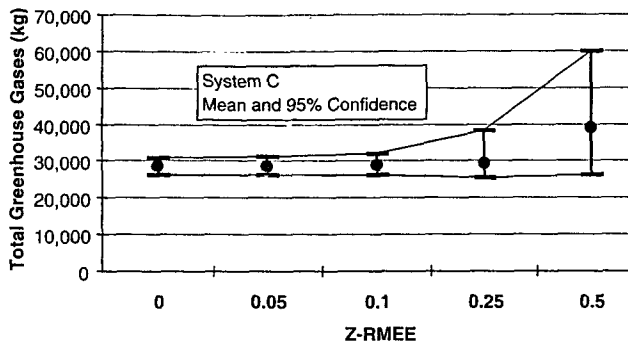
Fig. 9: The relationship between the Z_{RMEE} value and mean with 95% confidence interval for System C. At $Z_{RMEE} = 0$, the only source of uncertainty is from uncertainty in the data

sources of pollutants are left outside the system boundary. The RMEE method increases the uncertainty in results as Z_{RMEE} increases to reflect the change in system boundary.

Comparison of Applying the Numerically Generated Probability Distribution Function and the Truncated-Normal Distribution

For widespread application of the RMEE method, the tool must be practical. As a result, it is desirable to utilize a probability distribution function, which approximates the numerically generated distribution from this research. It is generally accepted that the normal distribution is one of the more readily applied distributions in engineering and science. To approximate the skewed distribution of Y_{ZMean}, this analysis uses a normal distribution truncated at $Y_{Zmean} = 100$ where any values greater than 100 are placed at the 100 boundary. Fig. 9 illustrates the distribution being used compared to the shape of the numerically generated distribution illustrated in Fig. 8.

Fig. 10 illustrates the difference between using the numerically generated probability distribution function for Y_{ZMean} in equation 3.2 and using a truncated-normal distribution. The comparison tends to indicate that using the truncated-normal distribution results in a more conservative approximation of the 95% confidence interval. Fig. 10 also shows that as Z_{RMEE} increases, the overestimation of the truncated-
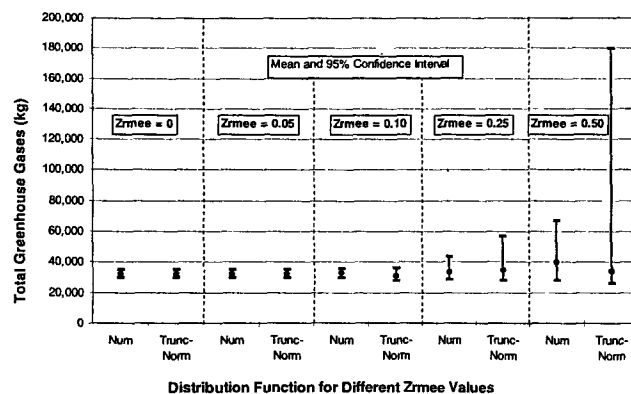

Fig. 10: Comparison of applying the Truncated-Normal (Trunc Norm) distribution function to the numerically generated distribution function (Num) for various Z_{RMEE} values. The values shown represent the mean and 95% confidence interval for System B

normal increases. At $Z_{RMEE} = 0.50$, use of the truncated-normal distribution greatly overestimates the uncertainty estimated by the numerically generated distribution. However, at Z_{RMEE} values between 0.05 and 0.25 (these are the values of Z_{RMEE} of most interest – see section 3.3.2 above), use of the truncated-normal distribution provides a conservative representation of the numerically generated distribution, but does not appear to greatly overestimate the uncertainty.

Because the truncated-normal distribution results in a conservative approximation of the 95% confidence interval and is relatively easy to generate, it is recommended that this distribution be applied for the RMEE method. This will help ensure the RMEE method is practical for LCA application. As a result, the remainder of this research applies the truncated-normal distribution for the distribution of Y_{ZMean} when applying Monte Carlo Analysis to equation 3.2.

Applying the RMEE Method to Compare Two Systems

Consider the LCA practitioner who decides to begin with a Z_{RMEE} value of 0.25. This means any flow in the system with a mass, energy and market value which is less than one-quarter of the functional unit's mass, energy and market value will be left outside the system boundary. The calculated results at $Z_{RMEE} = 0.25$ for System B and System C are shown in Fig. 11 with mean (X_{25j}) and uncertainty (r_{data}). These results are based only on the calculation of greenhouse gases from available data. No adjustment has been made to the results for system boundary selection. The results show System C to result in less greenhouse gases with partial overlap of uncertainties.
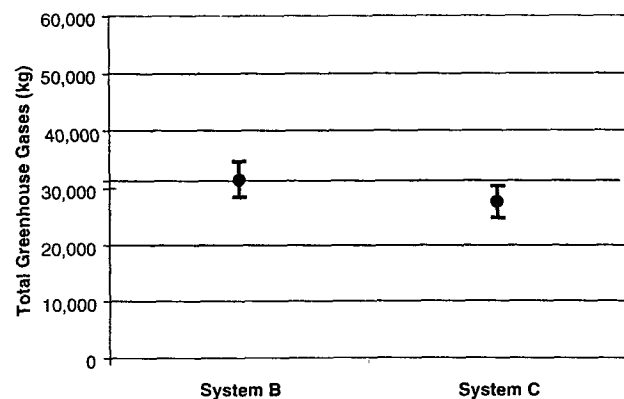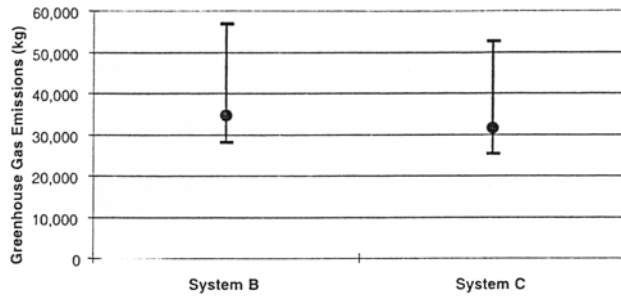

Fig. 11: Mean and 95% confidence interval of System B and System C at $Z_{RMEE} = 0.25$ before adjusting for system boundary selection

The next step is to adjust the initial calculated mean and uncertainty to take into account system boundary selection. This is accomplished by using Monte Carlo Analysis to combine the distribution of Y_{25Mean} and the distribution of X_{25j} for each system. The "RMEE Adjusted" comparison between System B and C after accounting for the system boundary are shown in Fig. 12. This result has been generated using the truncated-normal probability distribution function for Y_{25Mean}.

The results at $Z_{RMEE} = 0.25$, illustrated in Fig. 12, show a significant overlap of uncertainties. Although a decision maker may typically visually assess the degree of overlap in uncertainty and a make a decision, it is helpful to quantify the probability one option results in less environmental output than another.

Fig. 12: RMEE adjusted comparison of the mean and 95% confidence interval of greenhouse gases from System B and System C at Z_{RMEE} = 0.25 using the truncated-normal probability distribution function

One can quantify the probability that System C is less than System B. If the results from each system are normally distributed with the same standard deviations, one can use the normal distribution tables to quantify the probability the mean emissions from System C are less than the mean emissions from System B. Area (I) in **Fig. 13** represents this probability.

However, because the distribution of X_{Zj}' is not normal, Area (I) is best approximated by placing the results of the Monte Carlo Analysis into histograms and numerically calculating Area (I). Area (I) estimates the probability of the mean of System C being less than the mean of System B and is calculated using Equations 3.3 and 3.4.

$$Area(I) = \sum_{i=1}^{N}(F_i^C - F_i^B) \qquad (3.3)$$

F_i^C = Frequency of the Environmental Output of System C in Bin i

F_i^B = Frequency of the Environmental Output of System B in Bin i

N = Number of Bins in the histogram.

$$P(P_{ZC} < P_{ZB}) = \frac{\sum_{i=1}^{N}(F_i^C - F_i^B)}{\sum_{i=1}^{N}(F_i^C)} = \text{Probabilty } P_{ZC} \text{ is less than } P_{ZB} \quad (3.4)$$

P_{ZC}, P_{ZB} = Mean environmental Pollutant Output of System C and B.

Applying this technique to Systems C and B at Z_{RMEE} = 0.25 results in a 57.5% probability of the mean of System C being less than the mean greenhouse gas emissions of System B. For decision making, one may wish to expand the system
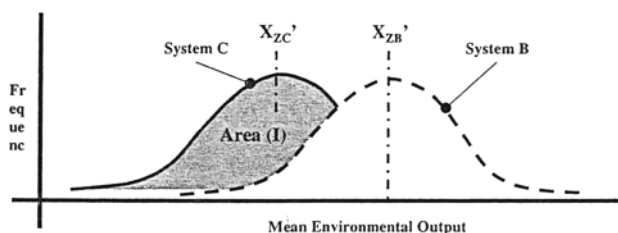
Fig. 13: Area (I) represents the probability the mean of System C (X_{ZC}') is less than the mean of System B (X_{ZB}')

boundary in order to further reduce the uncertainty in the decision. This is completed by reducing Z_{RMEE} and re-evaluating the system.

Fig. 14 presents the comparison at Z_{RMEE} = 0.10. At Z_{RMEE} = 0.10, the system is expanded to the point at which the uncertainty associated with system boundary selection is significantly reduced. It is found to be 64.7% probable that the mean of System C will be less than the mean greenhouse gas emissions of System B. At this point, the decision maker has greater confidence in making the decision, but may still wish to further expand the system boundary.
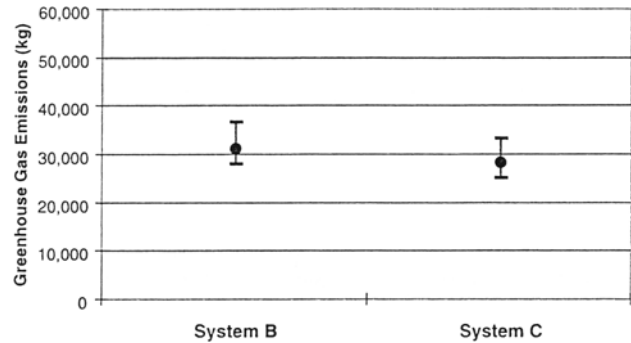
Fig. 14: RMEE adjusted comparison of the mean and 95% confidence interval of greenhouse gases from System B and System C at Z_{RMEE} = 0.10 using the truncated-normal probability distribution function

If the boundary is further expanded by using Z_{RMEE} = 0.05, the uncertainty is further reduced as shown in **Fig. 15**. At this level of detail, the results show it is 76.2% probable that the mean of System C will be less than the mean of System B. To further reduce uncertainty requires reducing the uncertainty in data.
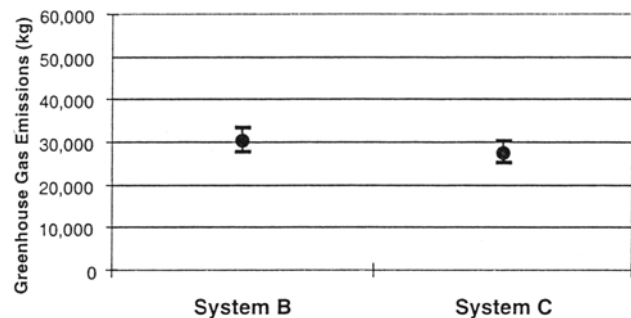
Fig. 15: RMEE adjusted comparison of the mean and 95% confidence interval of greenhouse gases from System B and System C at Z_{RMEE} = 0.05 using the truncated-normal probability distribution function

5 The RMEE Adjustment for a Significantly Different Type of System

The results presented here were developed by analyzing a large number of random systems which followed specific rules, defined in the section above entitled "Random System Generation". These rules require each unit process to conserve mass. This would be true for a typical manufacturing or material handling unit process. However, in the prac-

tice of LCA, some unit processes exist which do not conserve mass, due to the method of inventory assessment. For example, an LCA studying biomass production systems, such as corn production, would typically not have a mass balance because carbon from the soil and air, rain water, and many other naturally occurring nutrients which produce the corn are not normally accounted for in the life-cycle inventory. As a result, unit processes exist which produce a high mass product with relatively minor levels of measured inputs such as diesel fuel, fertilizers, and pesticides.

To test the impact on the RMEE method of unit processes which do not balance mass, two hundred systems were generated using the same rules as above, except that the mass ratio of inputs to outputs for any unit process could range from 0.1 to 5. In other words, a unit process could produce more mass in products than the measured mass of inputs. The results for this scenario are shown in Fig. 16 and Table 3, where it can be seen the average fraction of environmental outputs measured within the system boundary decreases more rapidly with the increase in Z_{RMEE}. The numbers presented in Table 2 for non-biomass systems, Y_{zMean} crosses the 90% level at $Z_{RMEE} = 0.4$, while for the biomass systems presented in Table 3, Y_{zMean} crosses the 90% point much earlier at $Z_{RMEE} = 0.2$.
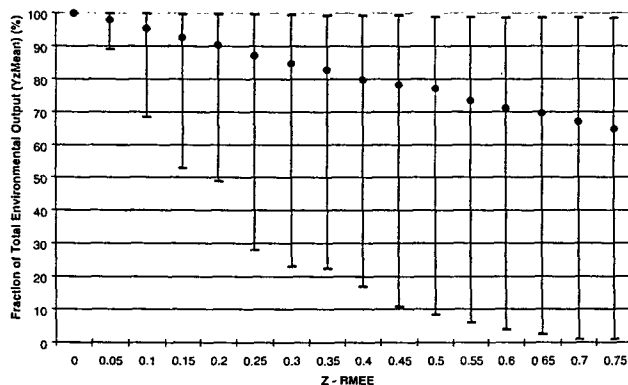

Fig. 16: Mean and 95% confidence interval for the fraction of total environmental output (Y_{zMean}) reported at different Z_{RMEE} values for biomass type systems

Table 3: Mean and 95% confidence interval of the fraction of total environmental output for different Z_{RMEE} values for biomass type systems

Cut-Off Ratio (Z_{RMEE})	Percentage of True Total Environmental Output			Standard Deviation
	Mean (Y_{zMean})	High (Y_{zHigh})	Low (Y_{zLow})	S_{RMEE}
0	100.00	100.00	100.00	0.00
0.05	98.01	99.95	89.00	3.06
0.10	95.44	99.91	68.50	7.89
0.15	92.66	99.86	53.00	12.21
0.20	90.48	99.81	49.00	13.51
0.25	87.05	99.71	28.00	17.62
0.30	84.85	99.62	23.00	18.79
0.35	82.69	99.38	22.50	19.78
0.40	79.77	99.38	17.00	22.62
0.45	78.18	99.29	11.00	23.96
0.50	77.08	99.00	8.50	24.38

In summary, the RMEE method provides a method of quantifying the uncertainty associated with system boundary selection. However, the results presented here show some influence of the nature of the system, particularly for systems which deviate greatly from the norm.

6 Conclusions

- The RMEE method of system boundary selection allows for the quantification of system boundaries and the evaluation of the uncertainty due to system boundary selection which is introduced to the results of an LCA. RMEE has been specifically designed and tested for energy and product systems in which an evaluation is being made on common combustion air emissions.
- The RMEE method provides an adjustment factor (Y_{zMean}) which can be used to adjust the results of an LCA to account for unit processes excluded from the system boundary at a chosen Z_{RMEE}.
- The uncertainty introduced from system boundary selection is related to Z_{RMEE} and increases as Z_{RMEE} increases. The relationship is shown in Fig. 5 and tabulated in Table 2.
- The probability distribution of Y_{zMean} is a skewed non-normal distribution.
- A truncated-normal distribution is considered to provide a fair representation of the numerically generated distribution (skewed non-normal) for Z_{RMEE} values less than or equal to 0.25.
- Monte Carlo Analysis is recommended as the most practical method to combine the uncertainty associated with Y_{zMean} and uncertainty due to data in X_{ri}.
- Calculating the probability the mean environmental outputs of one system is less than the mean of a competing system can be accomplished by comparing the histograms generated by the results of the Monte Carlo Analysis.
- The RMEE method provides consistent measures of system boundary related uncertainty for the most common classes of individual systems. However, production systems with significantly different characteristics (such as biomass production systems) provide a wider range of uncertainty. This result is shown in Fig. 16 and tabulated in Table 3.

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(Refer to this reference for the contributions of other authors in the area of system boundary selection)

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